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Identification of Optimal Conditions for Dry Drilling (Analytical Approach to Prediction of the Occurrence of BUE)

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IDENTIFICATION OF OPTIMAL CONDITIONS FOR DRY DRILLING

(ANALYTICAL APPROACH TO PREDICTION OF THE OCCURRENCE OF BUE)

by

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Identification of optimal conditions for dry drilling

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Abstract

Lubrication is used during the drilling of aluminum to counter the formation of a built-up-edge (BUE), among other reasons. The elimination of the use of lubricants in drilling of aluminum is important because of the associated high costs of cleaning and disassembly involved in lubrication. The optimal conditions sought in this work include the elimination of the use of lubricants along with the possible attainment of a high material removal rate, which could help in reduction of cost and increase productivity at the same time. BUE has been found to be almost always present in the process of metal cutting at low to moderate speeds. It has been found that a necessary condition for the formation of a BUE is the presence of a negative stress gradient away and normal to the tool rake face. The quantitative equivalence of the effects of temperature and strain rate on flow stress described by the Zener-Hollomon parameter (Z) [5]. The relationship between the Zener-Hollomon parameter (Z) and chip flow stress implies that a negative Z gradient could be considered equivalent to a negative stress gradient. A series of computer simulations with varied cutting conditions were analyzed to determine the combination of machining variables which yielded a low predicted BUE preferably with a high material removal rate. The results presented here include cases which have a low predicted BUE as well as a high material removal rate.

Introduction:

Identification of optimal machining conditions would allow us to perform dry drilling accurately, efficiently, and most importantly, at lower labor costs. In general, the goals of an ideal drilling process could be summarized as follows:

- ensuring specified dimensional control,
- cut with a high material removal rate(the product of cutting speed and feed) and,
- minimization of labor costs involving the use of lubricants.

One of the most important factors affecting dimensional control that requires the use of lubricants is the formation of a BUE. BUE is a small piece of work material that gets attached to the cutting edge during machining at low to moderate speeds. The formation of a BUE results in uncertainty in the cutting conditions, resulting in uncertainty in cutting forces. This could lead to decrease in quality of surface finish, variable cutting depth, and possible increase in tool wear. Thus the elimination of BUE is one of the most important steps in achieving our goals for dry drilling as outlined above.

There are methods currently available to eliminate the formation of a BUE. One could machine at very high speeds. Higher cutting speed generates a higher cutting temperature, which was found to eliminate BUE. The use of lubrication has also been found to be an efficient way to eliminate or mitigate the formation of a BUE. However, higher cutting speeds result in decreased tool life, and the use of lubrication results in higher labor costs. A low presence or complete absence of BUE at conventional cutting speeds would allow us to perform dry drilling efficiently. A reliable method to predict the conditions of occurrence of BUE would help us in the selection of desired cutting conditions.

The formation of a BUE on the cutting edge is due to a complex combination of the physical conditions including the work piece and tool material properties, that are present during the machining process. Research so far indicates that a necessary condition for the formation of a BUE is the presence of a negative stress gradient away from and normal to the rake face [7]. Such a stress distribution is believed to cause the chip to shear at a weak plane inside the chip, resulting in the formation BUE, as opposed to shearing at the chip-tool interface, which is the desired condition. Another cause that was studied in detail by researchers is adhesion between chip and tool, which may drag some of the chip material down to form a BUE. Our approach is based on the negative stress gradient hypothesis, which has been studied in detail and used successfully in many cases to predict the occurrence of a BUE [6].

The stress-strain relationship during the process of plastic deformation is influenced chiefly by temperature and strain rate [4]. A high cutting temperature results in thermal softening of the work material, preventing the hardening of chip material along the tool-chip interface. A high strain rate, on the other hand, results in work hardening, thereby increasing the flow stress along the tool-chip interface. The opposing effects of temperature and strain rate on the flow stress could be described as follows—decreasing the temperature at a fixed strain rate has the same effect as does increasing the strain rate at a fixed temperature on flow stress.

The opposing effects of strain rate and temperature were combined to form a single parameter affecting the stress-strain relationship. The observed relation between stress and strain in the plastic region is observed affected by high strain rate. In a study [5] conducted to validate the proposed equivalence of the effects of strain rate and temperature, the following relation was validated experimentally:

$$Z = \dot{\varepsilon} \exp(Q / RT)$$

where Z is referred to as the Zener-Hollomon parameter, $\dot{\varepsilon}$ is the strain rate, Q is a material characteristic with a heat of activation, R is the universal gas constant, and T is the absolute temperature in degrees Rankine. The above equation is based on the consideration that mechanical properties must be based on a single dimensionless quantity [5].

The above equation refers to the stress-strain relation at room temperature. The heat of activation Q was found to nearly the same for all steels with carbon content greater than 0.08 percent, ranging from 90 to 120 calories/gram mole. The isothermal stress-strain relation is used to determine residual stresses. At the tool rake face, the temperature is so high that very little time is allowed for heat conduction. Hence during the shearing of the chip, the stress-strain relation can be adiabatic. Adiabatic strain causes increase in stress, due to strain hardening, whereas the associated rise in temperature, causes thermal softening. Experiments [5], have found that the latent energy absorbed is about 15%. In this paper, we are mainly concerned about the isothermal stress-strain relationship because of the presence of residual stresses.

For a variety a metals, including aluminum alloys at steady state conditions, it is observed that a dynamic balance between work-hardening and thermal softening exists. This leads to a relationship between strain rate and flow stress [4] shown below:

$$\dot{\varepsilon} = A\sinh(\alpha_1\sigma_f)\exp(-Q/RT)$$

where σ_f is the flow stress and α_1 and A are experimentally determined constants. Combining the above two equations leads to the following equation, which describes the correspondence between flow stress and the Zener-Hollomon parameter.

$$Z = A\sinh(\alpha_1\sigma_f)$$

In other words, the correspondence between flow stress and the Zener-Hollomon parameter suggests that the distribution of Z could help us predict the distribution of flow stress, which in turn can help us in the prediction of the occurrence of BUE. This criterion was used historically with success in creep tests as well as for hot deformation of metals[4]. Howerton, Strenkowski, and Bailey [6], first applied it successfully to metal cutting.

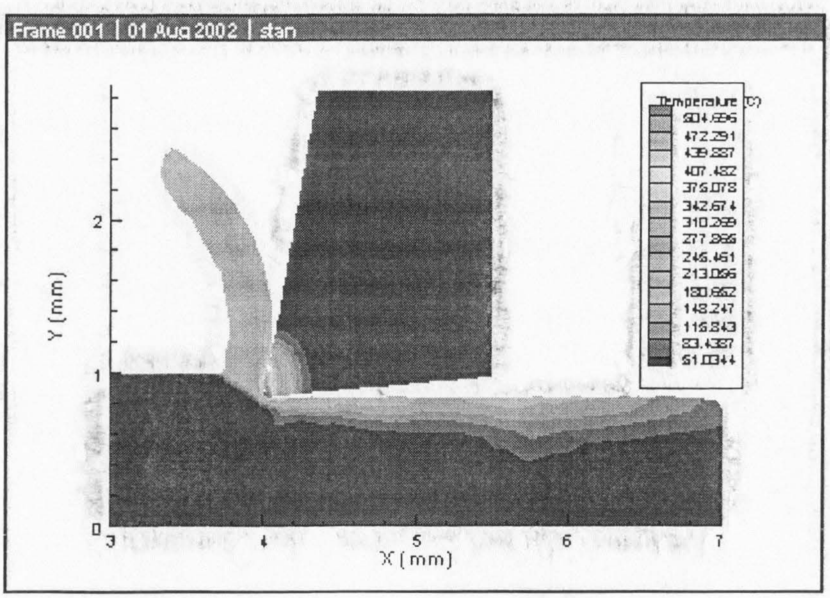
<u>Design of Experiments:</u>

A set of experiments was designed to span the parameter space which would include the cutting conditions currently being used at Boeing as inputs for metal cutting simulation. The following is the list of independent variables along with their range and units.

- cutting speed (0 to 5000) (ft./min.)
- feed (2 to 6) (1/1000in.)
- rake angle (-10 to 40) (degrees)
- cutting edge radius (0.25 to 2.0) (1/1000in.)

The two-dimensional simulation of the metal cutting process accepts these independent variables as input. The simulations were run using Mach2D™ , a Finite Element simulation software package , developed by Third Wave Systems™ . The software allows specification of the material model, cutting tool, work-piece, and process parameters including feed, speed, rake angle, cutting edge radius and, initial temperature. The simulation software was used to create a database of cutting process variables such as temperature, velocity, etc. The following is a snapshot of a simulation performed with Mach2D™ software.

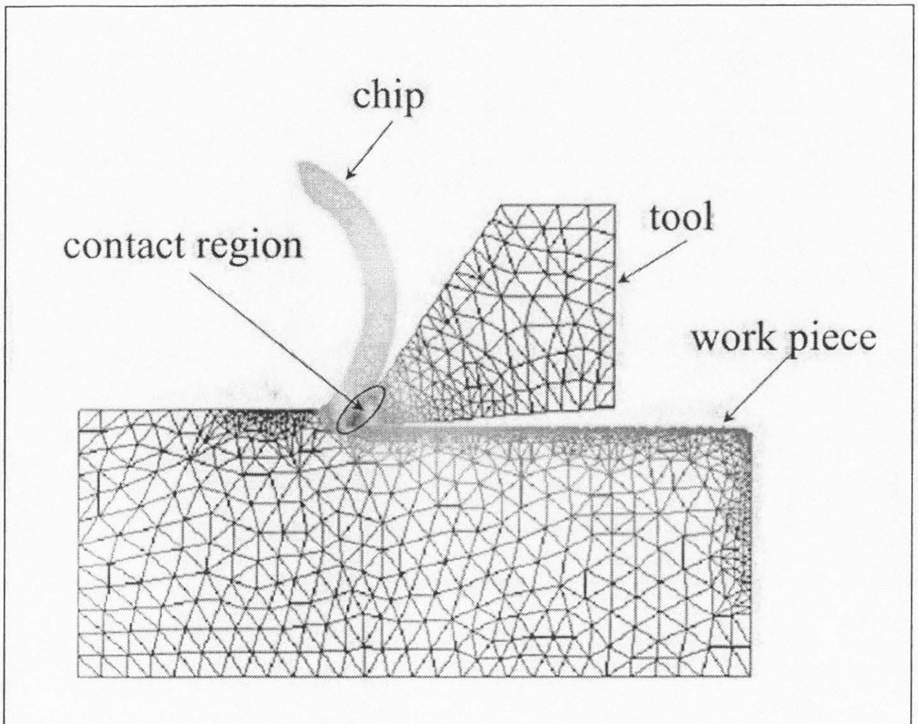
Figure 1



Snapshot of two-dimensional metal cutting simulation.

The picture shows the tool, the work piece, and the chip, along with the axes showing the dimensions. The column of temperatures shown in the picture corresponds to the temperature contours. The triangular finite element mesh was obtained from the last zone of the simulation for analysis. Each node on the mesh contains values of the process variables at that time, including plastic strain, plastic strain rate, and temperature, among others. BUE is assumed to form along the contact region on the tool-chip interface which is the region of interest for calculation purposes. The following diagram shows the finite element mesh obtained from the simulation, the various components and the contact region.

Figure 2



Triangular mesh obtained from the last zone of the simulation run(obtained from AVS Express™ visualization software.

Analysis and Results

The simulation output consists of files containing the nodal information for each zone as well as material properties. For each run, the finite element mesh was obtained from the last zone of the simulation, i.e., when the cutting process reaches a steady state. The mesh consists of triangular elements with each node of the element containing the following information:

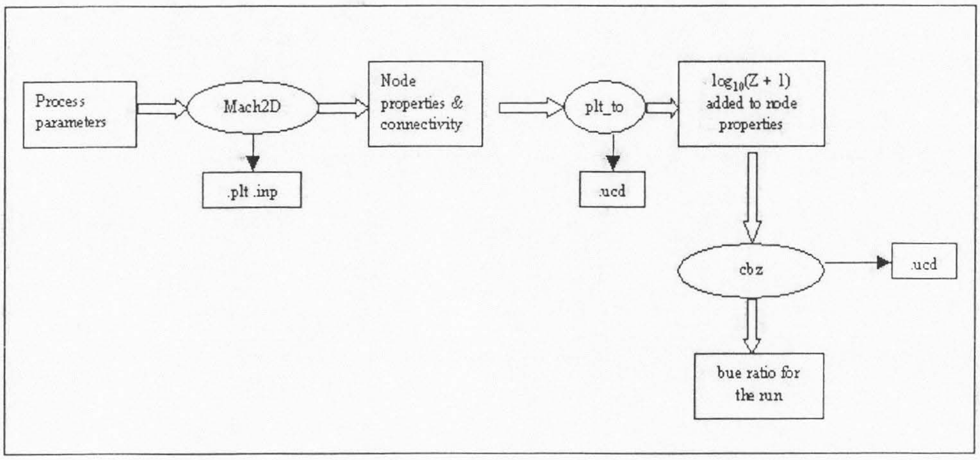
Table 1

Temperature ,C
Heat Rate ,W/mm^3
Plastic Strain, dimensionless
Plastic Strain Rate ,/s
Mises Stress , MPa
Pressure ,MPa
Max Shear Stress ,MPa
Stress-XX , MPa
Stress-YY , MPa
Velocity-X ,m/min
Velocity-Y ,m/min
Velocity Magnitude ,m/min

Nodal data

The chart below describes the procedure used to analyze the simulation output.

Figure 3



The chart shows the process of obtaining the predicted value of BUE for each set of independent variables.

The chart above describes the flow of data and the sequence of execution of the software to run the simulation and obtain the predicted value of BUE. Mach2D accepts the independent variables (speed, feed, rake angle, and cutting edge radius) as inputs, along with other process parameters including the material type, etc. The simulation is then performed with the output showing each zone (snapshot) of the run with the physical properties at each node of the mesh. The next step in the process is to compute the value of Z for each zone or the last zone. This step is accomplished by the program plt_to, which accepts the plt and inp files as input and computes the value of logarithm of Z and creates the output in the form of an Unstructured Cell Data (UCD) file.
For each node, the value of Zener-Hollomon parameter (Z) was calculated using the relation

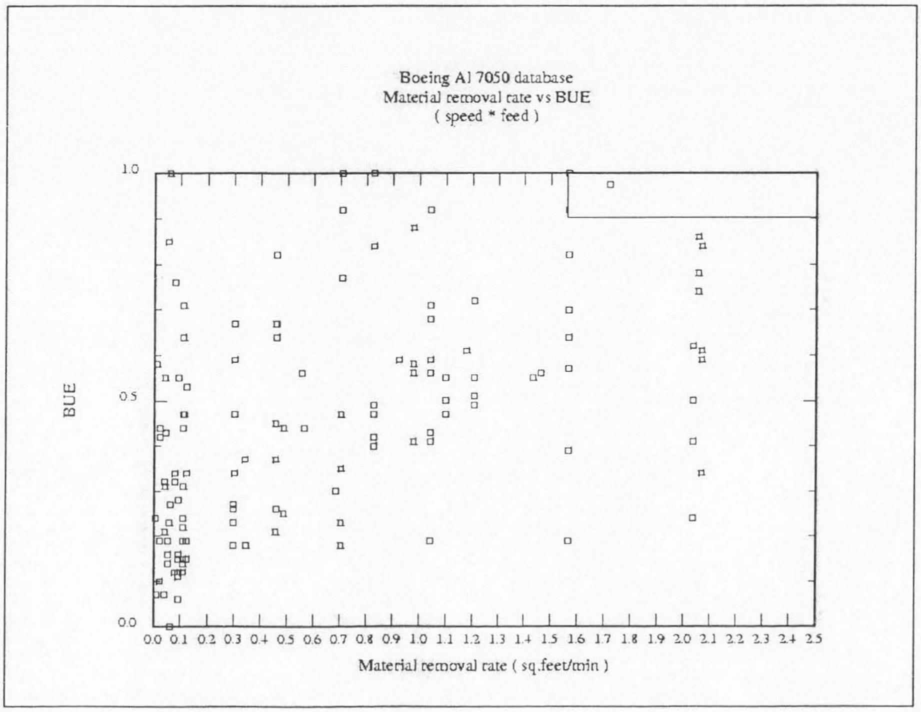
$$Z = \dot{\varepsilon} \exp(Q / RT)$$

using the values of plastic strain rate and temperature (converted to degrees Rankine) obtained from the simulation, and the value of Q = 151.0 BTU/mole and R=4.37 x 10^{-3} BTU/°R-mole[4]. Then, the gradient components of the $\log_{10}(Z + 1)$ were calculated. The next step is identify the contact region and calculate the ratio of BUE which is performed by the program cbz. To identify the contact region, all elements with significant plastic strain with edges having normals away and perpendicular to the tool rake face were selected to determine the contact region. The dot product of the gradient of Z and the normal vector for each element on the contact region was then calculated. The predicted BUE ratio (R) based on the Howerton [6] criterion was calculated using the relation shown below:

$$R = \frac{T_Z}{T_T}$$

where R is the calculated BUE ratio, T_Z is the total length of the element edges on the contact region with negative Z gradient components, and T_T is the total length of the element edges on the contact region.The calculation of the BUE ratio as described above was performed for each run. The following is a plot of the material removal rate versus the predicted BUE ratio.

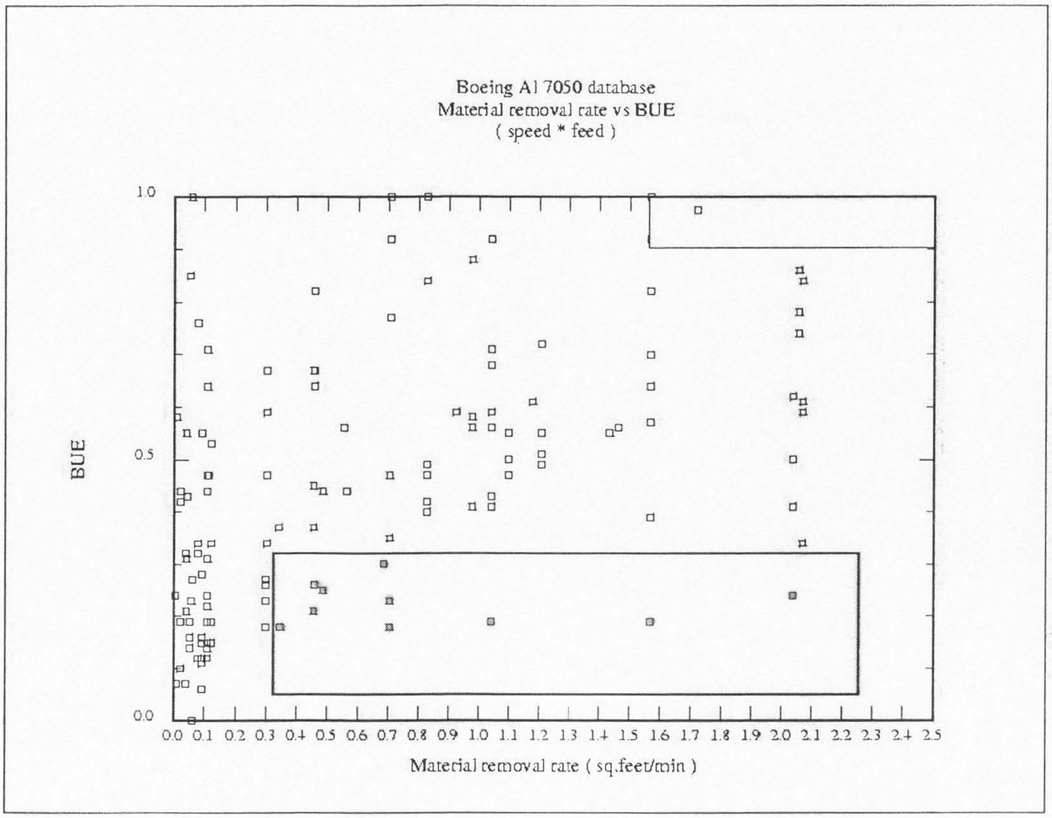
Figure 4



Material removal rate plotted against the predicted BUE ratio

The following is the same plot with the cases having relatively high material removal rate with a low calculated BUE ratio enclosed in a rectangle and shaded.

Figure 5



The rectangle shows the general region of interest with the cases within shaded red.

The table below summarizes the details of the cases shaded and enclosed within the rectangle in the above picture.

Table 2

speed	feed	mat.rem.rate	rakeangle	radius	bue
1366.14	3.07	0.35	1.00	1.51	0.18
1535.43	3.82	0.49	9.98	0.50	0.25
1836.61	4.49	0.69	4.41	0.76	0.30
2500.00	2.20	0.46	1.74	2.00	0.21
2500.00	2.20	0.46	18.31	2.00	0.26
2500.00	3.39	0.71	-8.00	0.25	0.18
2500.00	3.39	0.71	-8.00	0.50	0.23
2500.00	5.00	1.04	-4.08	0.50	0.19
4370.08	5.59	2.04	-6.21	2.00	0.24
4724.41	3.98	1.57	-4.03	2.00	0.19
ft./min.	1/1000in.	sq.ft./min.	degrees	1/1000in.	ratio

Selected low bue cases

Most of the cases in the above table have low or negative rake angles with high material removal rates. The variables speed, feed, rakeangle, and cutting edge radius, were the independent variables. The BUE ratio was the response variable. The DACE [8] model was chosen to represent the complexity in responses, assuming that the response is a realization of a Guassian stochastic process. The calculation of the effect importance and main effects for each independent variable was done Andrew Booker at The Boeing Company. The model can be represented by the following equation [8].

$$\hat{Y}(\vec{x}) = \sum_{i=1}^{N} w_i(\vec{x}) Y(\vec{s}^{\,i})$$

where $\hat{Y}$ interpolates the observations, $\vec{x}$ are the predicted values of the response variable and, $\hat{Y}(\vec{s}^{\,i})$ are the observations. Each w_i is the weight of the observed response from $\vec{x}$ (predicted response value) depending on how far away the the response is from $\vec{x}$ in the parameter space(feed, speed, rake angle and, cutting edge radius in this case.) The overall average of $\hat{Y}$ is

$$\hat{\mu} \equiv \int \ldots \int \hat{Y}(x_1, \ldots, x_n) dx_1 \ldots dx_n \ .$$

The main effects of each independent variable $\vec{x}_i$ is defined [8] as,

$$\hat{\mu}_i(x_i) \equiv \int \ldots \int \hat{Y}(x_1, \ldots, x_n) dx_{(i)} - \hat{\mu}$$

where $dx_{(i)}$ is short hand for

$$dx_1 \ldots dx_{i-1} dx_{i+1} \ldots dx_n ,$$

integration with respect to all variables except x_i. The function $\hat{\mu}_i$ is a function only of the variable x_i only. The functional analysis of variance approach gives the total amount of squared variation in the model $\hat{Y}$ about its mean is given by

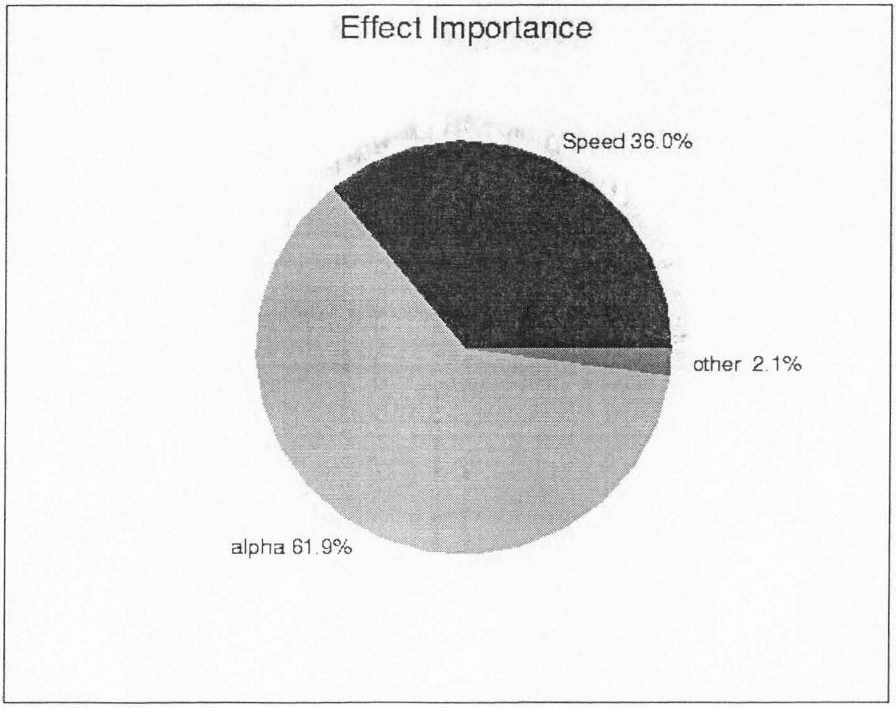
$$\int \ldots \int (\hat{Y}(x_1, \ldots, x_n) - \hat{\mu})^2 dx_1 \ldots dx_n \ .$$

The effect importance i.e. the proportion of contribution of $\hat{\mu}_1$ to the variation in $\hat{Y}$ about its mean is given by

$$\frac{\int \hat{\mu}_1^2}{\int \ldots \int (\hat{Y}(x_1, \ldots, x_n) - \mu)^2 dx_1 \ldots dx_n} .$$

The following picture shows the effect importance of the independent variables on the response variable i.e. BUE ratio.

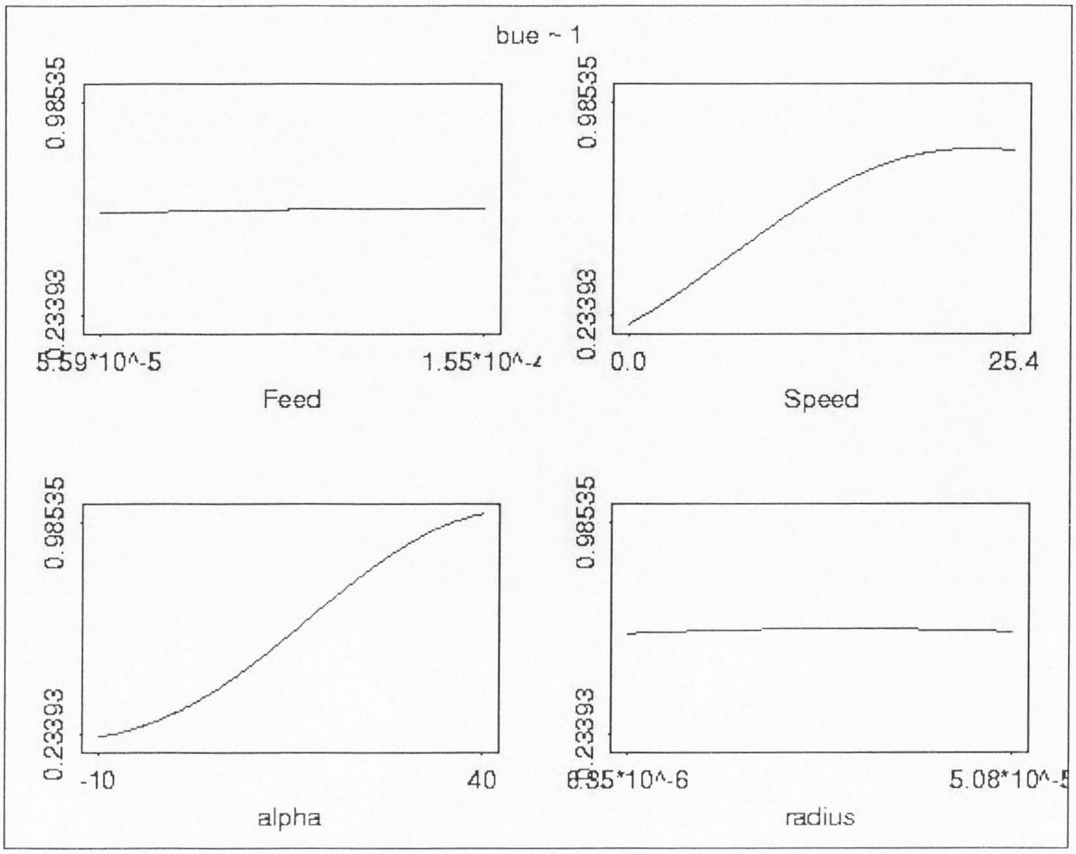
Figure 6



Effect importance of cutting speed, rakeangle (alpha), and others(cutting edge radius and feed) on the calculated BUE ratio- Graph created by Andrew J. Booker, The Boeing Company.

The picture above shows that while cutting speed affects the BUE ratio by 36.0%, the rake angle is a major influence on the BUE ratio with 61.9%. Feed and cutting edge radius (shown in the category "other") had very little effect on the predicted BUE. The plot of independent variables versus the response variable i.e. predicted BUE is shown below. Please note that the range of the variables is in S.I. units i.e. speed in meters/second, feed and cutting edge radius in meters.

Figure 7



Independent variables vs predicted BUE, all values are in S.I. units-Graph created by Andrew J. Booker, The Boeing Company.

The picture above shows that predicted BUE varies little with cutting edge radius and feed, whereas BUE varies in a linear/quadratic fashion with the predicted BUE. The simulations with the process parameters within the region of interest were repeated with the new version of the Mach2D™ software, Advantedge™ developed by Third Wave Systems Inc.™. The BUE ratio was calculated for both the last zone(steady state) and the one before that. The following table shows a summary of the results.

Table 3

speed	feed	mat.rem.rate	rakeangle	radius	bue(last zone)
1366.14	3.07	0.35	1.00	1.51	0.35
1535.43	3.82	0.49	9.98	0.50	0.60
1836.61	4.49	0.69	4.41	0.76	0.57
2500.00	2.20	0.46	1.74	2.00	0.70
2500.00	2.20	0.46	18.31	2.00	0.44
2500.00	3.39	0.71	-8.00	0.25	0.55
2500.00	3.39	0.71	-8.00	0.50	0.57
2500.00	5.00	1.04	-4.08	0.50	0.83
4370.08	5.59	2.04	-6.21	2.00	0.82
4724.41	3.98	1.57	-4.03	2.00	0.48
ft./min.	1/1000in.	sq.ft./min.	degrees	1/1000in.	ratio

Results of simulations repeated with same data

As is observed from the above Table2 and Table3, the calculated BUE ratio differs widely.

Conclusions

The analysis and results showed that indeed there are cutting conditions present at conventional speeds with a low predicted BUE. These cases are of interest and further investigation may reveal if there are cases within the neighborhood of the low BUE cases. The computed BUE values in Table 3 are different from those computed shown in Table2 because of reasons not known at the time of writing of this report. The suggested next step in finding the optimal conditions for dry drilling would be validate experimentally the predicted absence of BUE.

Acknowledgements

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